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PREPRINT

ON IMPROVING THE PENETRATION OF COMMERCIAL SHAPED CHARGE PERFORATORS

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ABSTRACT

Computational analysis demonstrated that the penetration of a shaped charge jet could be substantially enhanced by imploding the liner in a high pressure light gas atmosphere. The gas pressure helps confine the jet on the axis of penetration in the latter stages of formation. A light gas, such as helium or hydrogen, is required in order to keep the gas density low enough so as not to inhibit liner collapse. The computational analysis has now been experimentally confirmed.

INTRODUCTION

Modern shaped charges are widely used for both military and commercial applications. Although the main operation is remarkably similar in both applications, there are at least two significant differences in the devices actually employed. The first is cost. Military applications generally demand much higher performance and, in particular, high reproducibility. This, in turn, requires the liner to be forged and precision machined. The main commercial use is in oil or gas well stimulation, in which the jet from the shaped charge is employed to create a flow path from the reservoir to the wellbore. In this application, a large number of perforators is inserted into the wellbore in what is called a gun. Although there are three basic types of guns, perhaps the most common is the casing gun, which can be run into the well on a wireline or conveyed by tubing. The charges are contained in a steel tube, protected from impact and from the well fluids, and are arranged so that they face radially outward from the vertical axis of the carrier. In these devices, the liners are pressed using powder metal technology and are at least 2 orders of magnitude less expensive than those used in typical missile warheads.

The second factor that distinguishes commercial shaped charges from those used in weapons is standoff, i.e., the distance from the liner base to the target (usually measured in charge diameters). The penetrating effectiveness of a shaped charge jet is markedly enhanced by standoff. The reason for this is quite simple. Shaped charge jets normally are formed with a high axial velocity gradient, the tip moving at speeds of 6-10 km/s. The standoff distance allows the jet to stretch or elongate before encountering the target and, to first order, the depth of penetration is directly proportional to the length of the penetrator. There is an optimum standoff. If the distance to the target is too great, the penetration can be much less than if there were no standoff. This occurs because the jet can only stretch so much before breaking; once broken the particles are easily deflected by small perturbations and no longer produce a coherent, unidirectional penetrator. At optimal standoff, typically 6-8 charge diameters (CD), the penetration can be enhanced by 50% or more relative to that achieved with zero standoff. Commercial perforators, however, are rarely able to operate at more than 1 CD because they must fit inside the casing gun which, in turn, must fit inside the casing.

In what follows, we describe the results of a computational study of the effect of ambient pressure on shaped charge performance. We focus on a single (commercial) perforator, whose composite liner is a mixture of (mainly) metal powders. A constitutive model for the liner was devised and validated by comparing the calculated jet tip velocity with experimental data and the calculated penetration with measurements made in a well characterized (6061-T6 aluminum alloy) target. Next we we describe the results of a series of calculations of penetration into standard (API RP43) concrete targets in which only the pressure surrounding the perforator was varied. Although concrete is not a perfect surrogate for reservoir rock, it is not altogether dissimilar and by this means we were able to compare the predicted penetration with data from experiments in which the ambient pressure was atmospheric. Finally, we exhibit the superior results that were predicted when the surrounding air is replaced by helium and we conclude by briefly describing experiments that validated the predictions.

LINER CHARACTERIZATION

The perforator studied employed an OMNI conical shaped charge, manufactured by Halliburton Energy Services, Inc. The outer base diameter of the steel tamper is 46 mm. The explosive charge weighs 22.7 g and consists of 98.5-99% RDX, with the remainder being a wax filler. The liner consists of a mixture of tungsten (45.20% by weight), tin (11.05%), copper (43.19%), and graphite (0.53%) powders, together with a trace amount of lubricating oil. According to mixture theory, the density of the fully compacted liner should be 11.19 g/cm^3. Measurement of the actual density, using the method of Archimedes, yielded a value of 10.15 g/cm^3 (1), so that an initial gas porosity of 0.0929 was inferred.

A Grüneisen equation of state for the fully compacted powder was derived by D. A. Young of our Laboratory; the resultant parameters were: c_0 = 3.79 km/s, s = 1.592, γ_0 = 1.8, and b = 0.5. Here, c_0 is the bulk sound speed, s is the slope of the shock Hugoniot (in shock velocity-particle velocity space), γ_0 is the initial Grüneisen parameter, and b is the first order volume correction to γ_0.

All simulations described in this report were performed with the CALE hydrocode, developed at LLNL by R. Tipton (2). The pore compaction treatment in this code follows closely the standard p-α formulation initially devised by Carroll and Holt (3). In our model, we prescribed a Hugoniot elastic limit of 50 MPa, with complete pore crushup occurring at 161 MPa. No independent measurements were made of the liner strength so that, in effect, the strength model constituted a degree of freedom available to help fit the penetration data. We found that employing the standard Steinberg-Guinan ductile failure model available in CALE, with parameters mainly derived for copper, resulted in excellent agreement between predicted and measured jet tip velocity and in depth of penetration in (6061-T6) aluminum alloy targets; the experiments are described by Vigil (1).

Figure 1 shows the calculated penetration as a function of time, together with a snapshot crossection at 10 μs. The calculated jet tip velocity at this time was 6.4 km/s, the same value measured from the radiographs in the experiment. The final penetration was 265 mm, again in excellent agreement with the interpolated curve derived from the measurements (the calculation was performed at a standoff of 22.1 mm; the experiments were performed at standoffs of 6.35, 152.4, and 482.6 mm). The standoff position chosen for the calculations was the same as the position of the first target plate employed in the concrete penetration experiments, described below.

CONCRETE PENETRATION

Figure 2 illustrates the setup for the concrete penetration studies, which was chosen to replicate, as far as possible, the API Section 1 target. The outer boundary of the computational box was assumed rigid. The first steel target plate is supposed to simulate the gun wall and the second steel target plate butted up against the concrete is supposed to simulate the casing.

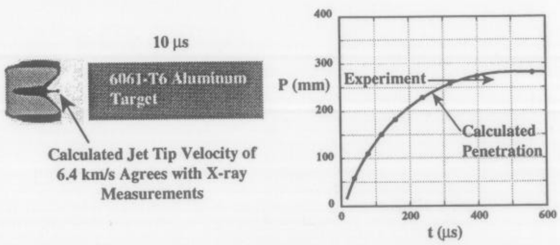

FIGURE 1. Calculations of jet formation and penetration in a 6061-T6 aluminum alloy target are in good agreement with SNL measurements (1).

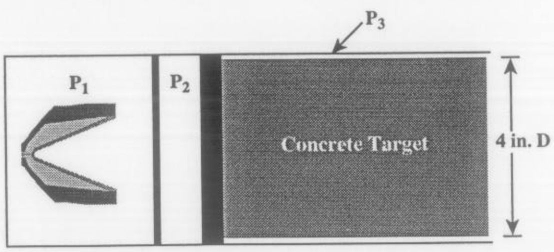

FIGURE 2. Setup for concrete penetration studies. Gas pressure was independently variable in 3 regions shown.

P_1 is the ambient pressure surrounding the perforator, P_2 is the pressure in the wellbore, and P_3 represents the reservoir pressure.

The concrete constitutive model employed is consistent with the specification for API RP43 Section1 targets and fits reasonably well the shock Hugoniot data reported for this material by Furnish (4). The initial gas porosity was assumed to be 0.18, corresponding to a density of 2.15 g/cm^3. The unconfined compressive strength was taken as 51.7 MPa (7,260 psi), and the strength increased with pressure up to a maximum of 160 MPa at a pressure of 1 GPa.

For the calculations discussed here, $P_2 = P_3 = 10$ MPa (1,450 psia). P_1 was varied from 0.01 to 69 MPa. With air, the penetration was observed to decrease monotonically with increasing ambient gun pressure, but the decrease was insignificant in the range $0.01 \leq P_1 \leq 10$ MPa. For higher P_1, penetration decreased dramatically and at 30 MPa, the liner collapse was inhibited by the formation of a high-pressure air bubble and even the steel casing was not completely perforated.

If a light gas such as helium or hydrogen is substituted for the air, the density can be reduced by an order of magnitude for the same initial pressure. Figure 3 illustrates the penetration obtained with helium; in these calculations, the reservoir and wellbore pressures were increased from 10 to 34.5 MPa (5,000 psia), which has the effect of increasing the strength of the concrete.

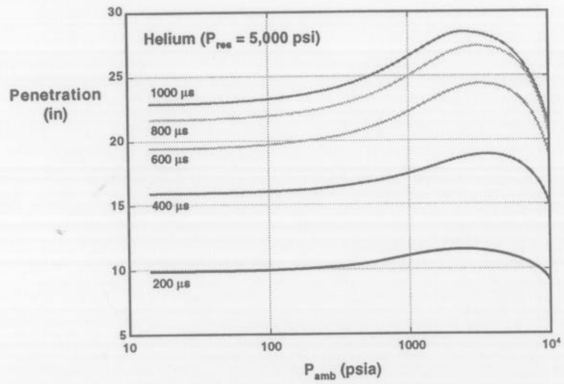

FIGURE 3. Calculated penetration as a function of internal (gun) pressure when helium is the_working fluid._

The maximum penetration in this case occurs roughly when $10 \leq P_1 \leq 35$ MPa. Figures 4 and 5 illustrate the physical basis for this increased performance. In both figures, the cross section of just the liner material for the calculations with higher P_1 overlay the liner cross section for $P_1 =$ 0.1 MPa (14.5 psia). Figure 4 shows the situation at 10 μs, when the jet tip velocity has attained its maximum value, prior to perforation of the first plate (gun wall). It is clearly observed that, as the initial helium pressure surrounding the liner is increased, the base of the jet is forced to recede and an increasingly narrow and elongated jet is produced.

Figure 5 depicts the liner profiles at 20 μs. As the initial surrounding pressure increases, the jets are seen to elongate and their cross sections diminish. When P_1 is 69 MPa (10,000 psia), the tip is still slightly ahead of the low-presure case, but the calculation shows evidence of jet breakup beginning to occur. Although there is no explicit constitutive model for breakup in the code, the interface treatment implicitly produces this effect when the cross section gets sufficiently small; gas and jet material are then intermixed, and the local density is concomitantly reduced which, in turn, tends to decrease penetration.

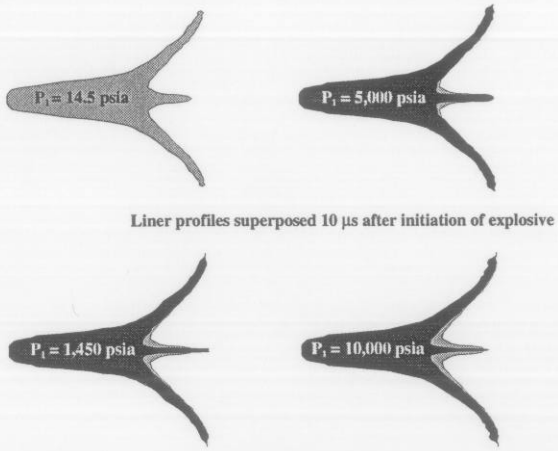

FIGURE 4. Increasing the helium pressure surrounding the liner produces and increasingly narrow and elongated jet.

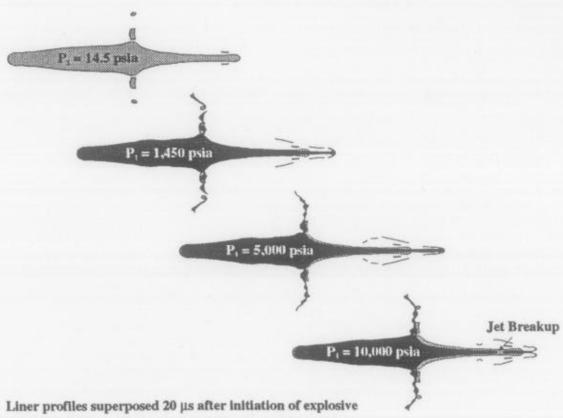

FIGURE 5. Increasing the helium pressure surrounding the liner stretches the jet and increases penetration depth in the target until jet breakup occurs.

EXPERIMENTAL VALIDATION

Experimental validation of the pressure enhancement concept was obtained in collaboration with D. Leidel and J. Barker at the Alvarado, TX facility of Halliburton Energy Services Co.

Two API Section 1 concrete targets were poured on the same day and cured for the same period. We inserted identical 5-foot long guns in each target. Each gun employed 37 4-5/8" OMNI perforators, the design of which was discussed above; shot density was 12 SPF, with 1 foot spacing at either end. One of the guns was operated with interior ambient (0.1 MPa) air pressure and the other with helium at 13.8 MPa (2,000 psia).

The average penetration from the 37 perforations with the helium system increased 40.3% over that obtained with the conventional system. The standard deviation was 11.3% of the mean penetration when the high-pressure helium was used and 12.9% when ambient air was employed. These results actually exceed the predicted improvement in performance, which assumed an ideal (axisymmetric) perforator. The high-pressure light gas surrounding the jet tends to inhibit instabilities that enable the jet to wander off axis and thus decrease penetration.

Additional experiments are planned to assess the repeatability of these results, to determine parametric response, and to explore scaleability to other perforating designs.

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